Annual Report:

Measurement of ecosystem metabolism across climatic and vegetation gradients in California for the 2013-2014 NASA AVIRIS/MASTER airborne campaign

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I. Project Overview

We are using the California transects for the ongoing HyspIRI Airborne campaign (Figure 1) to comprehensively assess the potential to make spatially explicit estimates of two important parameters characterizing leaf and canopy photosynthetic capacity: the maximum rate of CO_2 carboxylation by RuBisCo (V_{cmax}), and the maximum rate of electron transport required for the regeneration of RuBP (J_{max}). These variables are typically determined using direct, time-consuming leaf-level gas exchange measurements. However, in this project we are applying and refining rapid spectroscopic methods (at the leaf and the canopy scales) that we have been developing (Ainsworth et al., 2013; Serbin et al., 2012; Serbin et al., *in prep*) to estimate V_{cmax} and J_{max} over broad regions and across vegetation types found in California ecosystems (including managed agricultural lands). It follows that estimation of these variables from remotely sensed hyperspectral+thermal IR data can facilitate a better understanding of the spatial patterns and seasonal characteristics of vegetation carbon assimilation across complex landscapes using similar data to that anticipated with the NASA HyspIRI satellite mission concept. Our research relies on the simultaneous acquisition of hyperspectral and thermal infrared imagery, as estimates of canopy temperature will be crucial for an accurate characterization and scaling of V_{cmax} and J_{max} to allow for broad scale analyses as well as assimilation into ecosystem process models.

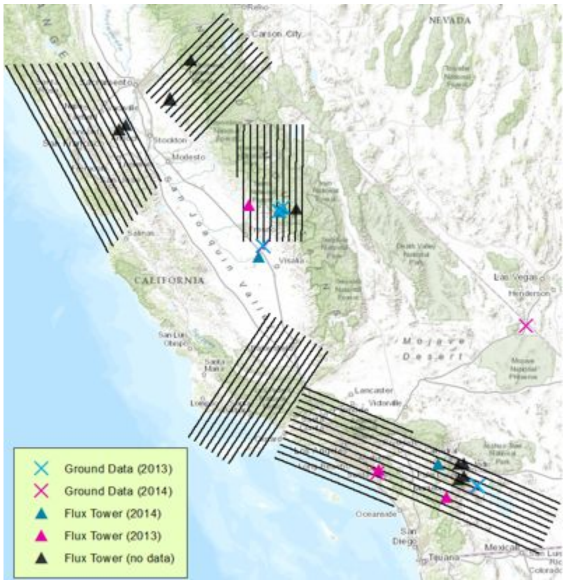

Fig 1. Study site locations and AVIRIS flightlines (see Table 1).

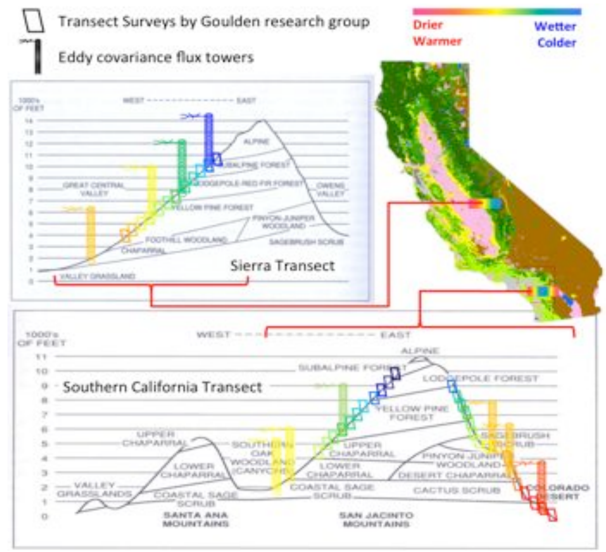

Fig 2. Climate-elevation gradient associated with our sampling design.

Our research focuses primarily on two climate-elevation gradients in California (Figure 2), spanning a vegetation gradient from desert chaparral to oak woodlands and high-elevation needle-leaf forests (Table 1). We are also collecting similar data at three key UC agricultural research stations to characterize globally important agro-ecosystems, in addition to natural vegetation. This provides us a strong gradient in which to test our methods and scaling approaches in a variety of vegetation types, demography, vegetation structure, and canopy functional properties. We are deriving our maps of canopy metabolism using empirical (partial least-squares regression modeling, Serbin et al., 2012) and mechanistic radiative transfer modeling (RTM) approaches with the raw AVIRIS+MASTER L2 data as well as simulated HyspIRI data being developed during the Airborne campaign. We are validating out simulated HyspIRI products of canopy metabolism using a suite of eddy covariance (EC) tower sites (Goulden et al., 2012; http://www.ess.uci.edu/~california/) located across our climate-elevation gradient (Table 1) by comparing estimates of derived from tower measurements of Gross Primary Productivity (GPP). Finally, we are also deriving and testing leaf-level estimates and maps of vegetation functional properties (pigments, nitrogen, carbon, and lignin) using algorithms previously developed across the Upper Midwest (Serbin et al., 2014; Singh et al., in prep). The idea is to test the generality of these methods to new locations as well as supplement our analysis to include properties known to influence vegetation productivity and nutrient cycling. This combined effort will yield considerable insight into the functioning of vegetation ecosystems throughout California.

Table 2. Core study sites

Site	**Latitude**	**Longitude**	**Elev. (m)**	**Vegetation**
Loma Ridge Coastal Sage (EC)	33.727	-117.693	480	Coastal sagebrush
Loma Ridge Coastal Grassland (EC)	33.727	-117.693	480	Coastal grassland
South Coast Research and Extension Center (Ag)	33.633	-117.677	88	Avocado, citrus

Sky Oaks (EC)	33.380	-116.630	1397	Montane chaparral
Coachella Valley Agricultural Research Station (Ag)	33.544	-116.147	-27	Red pepper, grape
Pinyon/Juniper (EC)	33.592	-116.448	1208	Pinyon pine, juniper
Desert chaparral (EC)	33.596	-116.445	1171	Arid chaparral
San Jacinto James Reserve (EC)	33.803	-116.753	1325	Oaks, cedar, pines
Kearney Agricultural Research Station (Ag)	36.573	-119.500	115	Pistachio
San Joaquin Experimental Range (EC,N)	37.079	-119.720	352	Foothills pine, oaks, annual grasses
Kingsburg Agricultural Center (EC, Ag)	36.458	-119.579	86	Peach, almond
Soaproot Saddle (EC,N)	37.029	-119.256	1166	Ponderosa pine, oak
Providence Creek (EC)	37.067	-119.195	2016	Mixed conifer
Shorthair (EC)	37.067	-118.987	2703	Lodgepole pine, Sub-alpine fir

EC: Site with eddy covariance flux tower; Ag: Agricultural site; N: NEON site

II. Progress Report

Overall Project Plan

The overall project contains these primary objectives, which are organized according to a set of interacting activities that are illustrated in Figure 2 below:

(A) Derive V_{cmax} and J_{max} at the leaf level by the combination of spectroscopy (leaf reflectance and transmittance) with combined gas exchange and chlorophyll fluorescence measurements (using the LiCor 6400 with the LI6400-40 leaf chamber fluorometer) at the study sites (Table 1, Figure 2). We are currently combining these measurements with a similar dataset from the Upper Midwest (Ainsworth et al., 2013; Serbin et al., 2012; Serbin et al., *in prep*) to develop a generalized algorithm for determination of leaf metabolism;

(B) Scale leaf-level estimates of V_{cmax} and J_{max} to the canopy using measurements of canopy composition and structure in conjunction with an empirical PLSR and radiative transfer modeling approach using the 4SAIL2 model (Verhouef and Bach, 2007). Because the rate of photosynthesis (and thus the values of V_{cmax} and J_{max}) is highly temperature dependent, we are utilizing the MASTER data to properly retrieve the metabolic parameters and scale to a common temperature (V_{cmax} and J_{max} at 25 °C). Our RTM approach is based on a lookup table (LUT) inversion method that accounts for the uncertainties in measurements and the RTM;

(C) Inform a simple ecosystem model with EC tower observations of net ecosystem exchange of CO_2 (NEE) and inferred GPP through a Bayesian parameter inversion to estimate tower-scale V_{cmax} and J_{max}. These data are used to evaluate the maps of photosynthetic capacity across space and time within the footprint of each EC tower;

(D) Utilize the validated maps of V_{cmax} and J_{max} to generate seasonal GPP maps across the HyspIRI flight boxes to diagnose the seasonal and spatial patterns of ecosystem productivity.

(E) Validate and utilize existing algorithms (Serbin et al., *in review*; Singh et al., *in review*) for mapping foliar chemical and morphological traits (N, C, lignin, SLA) to pair these maps with V_{cmax} and J_{max} to better understand ecosystem functioning and nutrient cycling across California.

Our work flow and conceptualization of how the pieces of our project fit together are illustrated in Figure 3. The numbers on Figure 3 will be used in the progress report below as a series of tables and text that report our accomplishments and ongoing work.

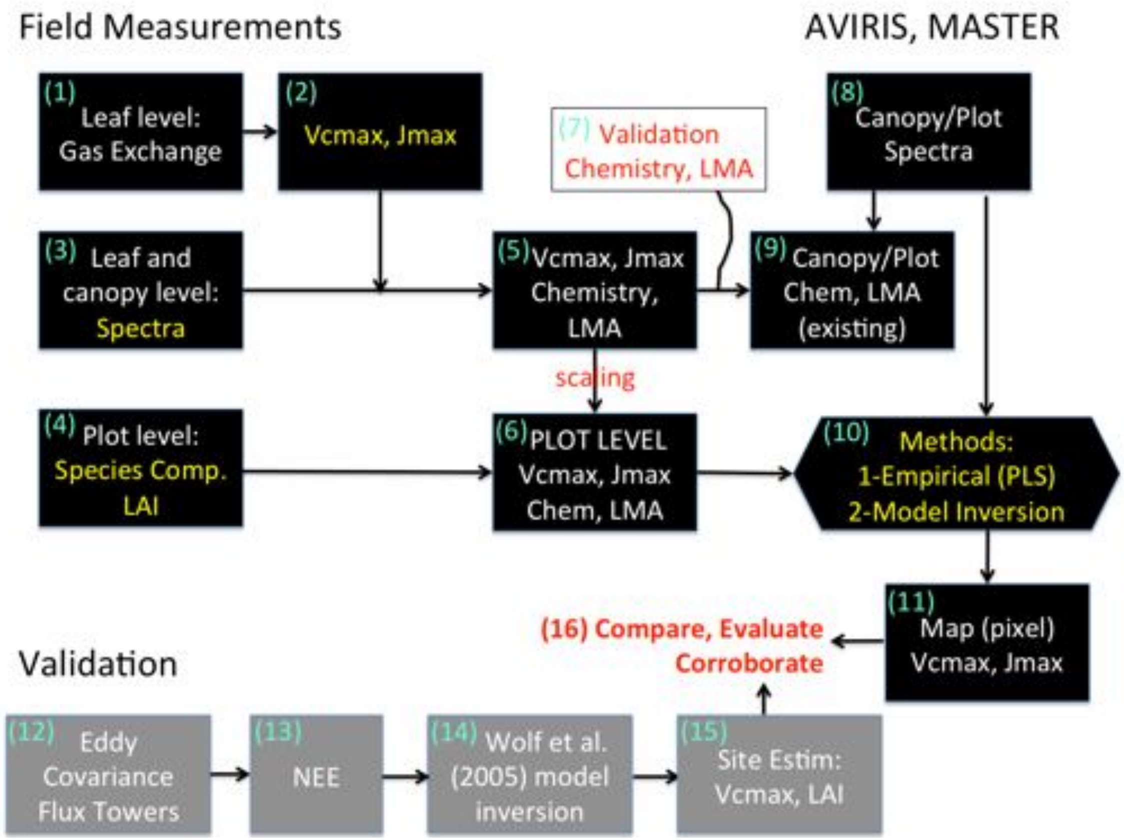

Fig 3. Project Workflow.

Our year 1 efforts focused on vegetation sampling across two HyspIRI flight boxes, the Southern California box and the Sierra/Yosemite box (Figure 1). We collected data within the footprints of the EC towers as well as within agricultural sites in order to capture the gradient in vegetation productivity across California. In Year 2, we resampled these locations and added new ones (all shown in Figure 1). We do not currently plan any additional intensive field campaigns (we've conducted four thus far), although we may make some targeted measurements during future acquisitions. ***Note that our field sampling efforts (and the number of sites we have visited per campaign) is not equivalent to our total sample size. Our sample size is actually the population of all flux towers by number of AVIRIS+MASTER acquisitions (likely 15-20 flux towers and 6 AVIRIS+MASTER campaigns, totaling as many as 150 data points], whereas the number of associated concurrent intensive ground measurements is somewhat lower [30].***

(A) Field Measurements

At each field sampled site, we have collected measurements of leaf gas exchange (combined A-C_i and chlorophyll fluorescence measurements), leaf temperatures, green-leaf reflectance and transmittance using an ASD FieldSpec3, Spectral Evolution PSM-3500, and an ASD integration sphere, as well as measurements of leaf mass per area (LMA) at three levels in the canopy (top, middle, and bottom, when relevant) at several plots. Upper canopy samples (top, middle) were collected using a line launcher equipped with a rope saw in order to harvest small branches for analysis. Leaf samples of foliar reflectance/transmittance and photosynthesis (e.g. Figure 3) are being used to develop the models for estimating V_{cmax} and J_{max}. In addition, we measured plot-level composition and structure at each sample site. Table 2 provides a summary of the measurements we take at each site.

Table 2. Summary of measurements made at each site

Measurement	**Methods**	**Observation**
Leaf reflectance & transmittance	ASD FS3, Spec. Evolution PSM-3500, ASD integrating sphere	Leaf optical properties, foliar traits (N, C, pigments, lignin, LMA)
Leaf photosynthesis	Li-6400 & 6400-40 fluorometer	V_{cmax} and $J_{max,}$ pigment quenching, electron transport rate (ETR)
Leaf weight, area	Analytical balance, flatbed scanner	Leaf mass per area (LMA), leaf shape (boundary layer), leaf water
Basal area, DBH, Height	Prism, DBH tape, laser hypsometer	Canopy composition and structure

Specific details on measurements and analyses associated with each box in the project workflow diagram in Figure 3 are provided in the tables and figures below. Table 3 summarizes the field measurements of leaf-level physiology, while Table 4 provides an overview of the associated leaf- and site-level spectral data that have been collected.

Table 3. Boxes (1) and (2) in Figure 3. Leaf level gas exchange (i.e., photosynthesis) measurements collected.

Campaign	# Sites	# Species	# Measure-ments	# Vcmax estimates	# Jmax estimates
Spring 2013	4	14	250	30	30
Early Summer 2013	7	15	1200	100	100
Late Summer 2013	no field sampling	no field sampling	no field sampling	no field sampling	no field sampling
Spring 2014	2	7	750	~75	~75
Early Summer 2014	5	12	1000	~100	~100
Late Summer 2014	TBD	TBD	TBD	TBD	TBD

PROJECT TOTAL	10	29	3200	~305	~305

Table 4. Boxes (3), (5) and (7) in Figure 2. Ground-based spectroscopy measurements.

Campaign	# Sites	# Species	# Leaf Reflectance Spectra	# Leaf Transm. Spectra	# Canopy Spectra	# Spectra tied to Vcmax/Jmax	# Spectra tied to chemistry
Spring 2013	4	14	1400	635	240	1150	250
Early Summer 2013	7	15	2500	800	150	1000	1000
Late Summer 2013	none	none	none	none	none	none	none
Spring 2014	2	7	1030	400	460	380	650
Early Summer 2014	5	12	1235	845	265	102	800
Late Summer 2014	TBD	TBD	TBD	TBD	TBD	TBD	TBD
PROJECT TOTAL	10	29	6165	2680	1115	2632	2700

<u>New Results</u> - Linking metrics of leaf photosynthetic capacity with reflectance spectra

A major component of our HyspIRI field campaigns entailed measurements of leaf gas exchange in conjunction with leaf optical properties, with the intent of building on our leaf-level dataset (Serbin et al., 2012) by adding measurements from the dominant species encountered at the various sampling sites. Importantly, the data expansion included an array of needle-leaf conifer species. We employed standard gas-exchange methodology to estimate photosynthetic metabolism; namely measurements of photosynthetic CO_2 response (A-C_i curves) with a Li-Cor LI-6400 portable photosynthesis system, combined with parameter optimization to estimate the maximum rates of RuBP carboxylation (V_{cmax}) and RuBP regeneration (J_{max}), based on the Farquhar-von Caemmerer-Berry ("FvCB") model of photosynthesis. At all sites, for every dominant species, we generated A-C_i curves across a range of leaf temperatures to calculate the temperature responses of V_{cmax} and J_{max}. Leaf gas-exchange assessments were accompanied by simultaneous measurements of leaf spectra using the FieldSpec 3 portable spectroradiometer with attached integrating sphere and leaf-clip assembly. An Agri-therm III infrared radiometer was used for measurements of leaf temperature prior to each spectral measurement. In both 2013 and 2014, all leaf measurements were conducted within 14 days of the corresponding AVIRIS/MASTER overflights.

While we are currently in the midst of data analysis, one critical finding has already emerged (related to box 5 on Figure 3): our general model predicting V_{cmax} and J_{max} solely on the basis of leaf optical properties appears to be effective for needle-leaf as well as broadleaf species (Figure 4). ***This result is further evidence for the potential utility and applicability of our approach across a broad range of C_3-dominated ecosystems.***

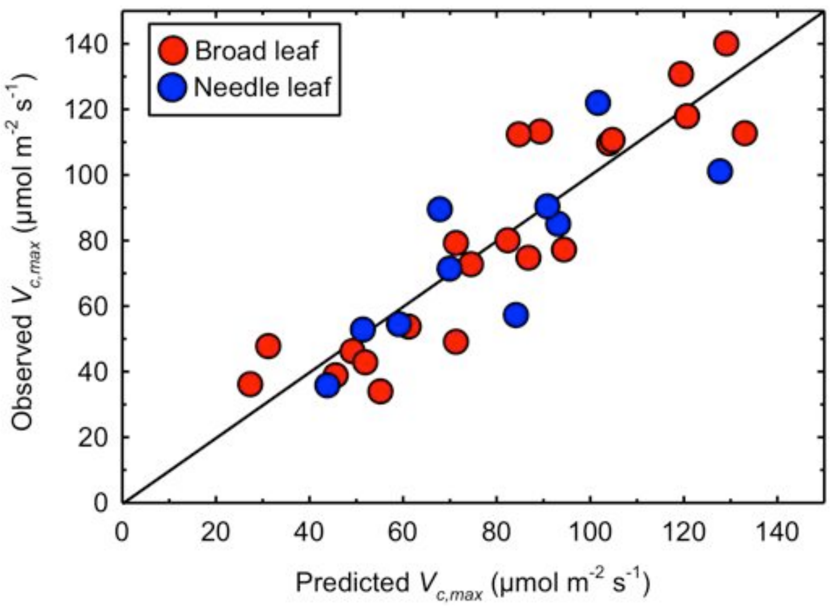

Figure 4. Observed values of V_{cmax} plotted against those predicted with a model based on leaf reflectance spectra. Broadleaf data are those used previously for validation of our general model. Needle-leaf data are derived from our HyspIRI California field campaigns and serve as a completely independent dataset.

(B) Flux Tower Analyses

In year 2 of the project, we continued to acquire and analyze eddy covariance flux tower observations in the footprint of the overflights and test algorithms for derivation of plant photosynthesis and photosynthesis parameters from the towers. Our two primary findings are:

1) Inversions of flux tower net ecosystem exchange observations for V_{cmax} degrade during drought. Assumptions about canopy scaling, flux footprint, nighttime respiration, and carbon-water coupling in these simplified models of plant photosynthesis and canopy scaling compromise the ability of these models to adequately retrieve parameters that are in the same range as leaf-level gas exchange. This effort will complicate comparisons to airborne retrievals, **but provides also a strong basis for why airborne retrievals are necessary and also provides insight into limitations of water-stress in current generation models**. We have also used these results to modify field experimental design to focus on the flux footprint.

2) The drought had a significantly strong impact on plant gross primary productivity at all sites. Surprisingly, sites that normally receive low precipitation were the most impacted by drought. These results provide a framework for evaluating temporal variability of airborne photosynthetic parameter retrieval and its relationship to water limitations.

These analyses are now in process of being turned into a manuscript and also form the basis of an M.S. thesis by project support graduate student Sean DuBois.
The flux tower sites used in this project all are located within the flight lines in which imagery is collected, including the sites managed by Mike Goulden. Potential sites include overflow towers managed by Dennis Baldocchi. Furthermore, we are coordinating with the USDA to add their sites that fall within the flight lines. The current focus is on the Goulden tower sites, which cover two vegetation climate gradients located in southern and central California, specifically the five sites for which we have collected leaf-level data.

We have processed the most up-to-date data supplied by the Goulden lab, including data from 2006 through the fall of 2013. The data were run through quality control measures to ensure the reliability of the observations. This includes the removal of any outliers in the data, and u-star filtering. The latter measure removes data for which there is insufficient turbulence for reliable eddy covariance data collection. Before conducting fieldwork, the flux data are analyzed to determine optimal sampling locations. Wind rose plots (Figure 5) were generated to determine the direction of the footprint, or location of vegetation the tower is measuring, for each site. In addition, a footprint model was used to determine the size of the footprint by estimating wind speed, canopy height, tower height, and other meteorological parameters. These provide us with a strong idea of where we should sample, ensuring the comparison between flux data and leaf level data is meaningful. ***In addition, these analyses help us to identify the AVIRIS/MASTER pixels to use for our comparisons with tower data.***

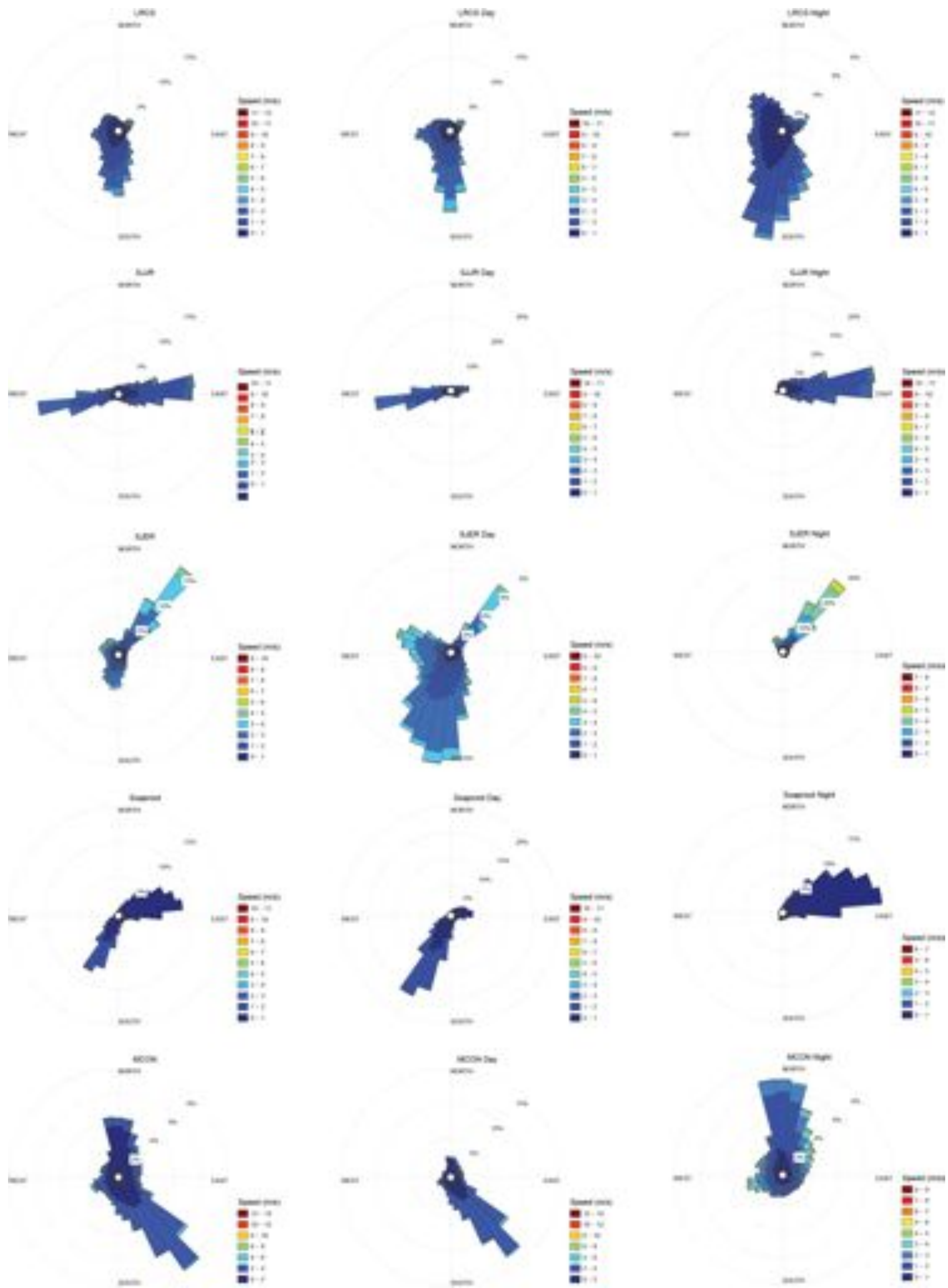

Fig 5. Wind rose plots for the five flux tower sites that have been visited. There figures were used to developing sampling strategies for each site.

We employed two models to assist in our understanding of the ecosystem and our evaluation of the imagery. These include estimating gross primary productivity (GPP) and the maximum rate of carboxylation (V_{cmax}). GPP was calculated by estimating respiration and subtracting that value from the carbon flux measured by the tower. The model employs the method of determining respiration from nighttime NEE and extrapolating that value via temperature to determine respiration during the day. This is done for all data points, and thus gives us GPP estimates at 30-minute intervals. V_{cmax} estimates from towers were generated from inversely solving a Farquhar and Ball-Berry photosynthesis model following Wolf et al. (2006). The model requires a multi-day data record, and therefore we can determine a single V_{cmax} estimate over several days, or the span of days spent at a site.

While the focus is on the time periods for which we visited the sites, the ability to examine these sites with some historical context allows us to determine the annual and seasonal variability of each site. A major impact on all sites is the presence of drought in California and the western US. Figure 6 below shows the extent to which drought limits growth in the ecosystems we have sampled. Sites that generally received little precipitation have been particularly harder hit, such as the Coastal Sagebrush. Forested sites tend to handle the drought better, and are able to reach production rates similar to pre-drought conditions (2011) in cooler months. When the water demand increases with warmer temperatures, there is a precipitous decline in GPP for these forested sites, including the Oak/Pine Forest and the Ponderosa Pine Forest. ***One of our primary objectives for Year 3 is to determine whether the drought signal apparent in the flux data is represented in retrievals of physiological parameters from AVIRIS/MASTER.***

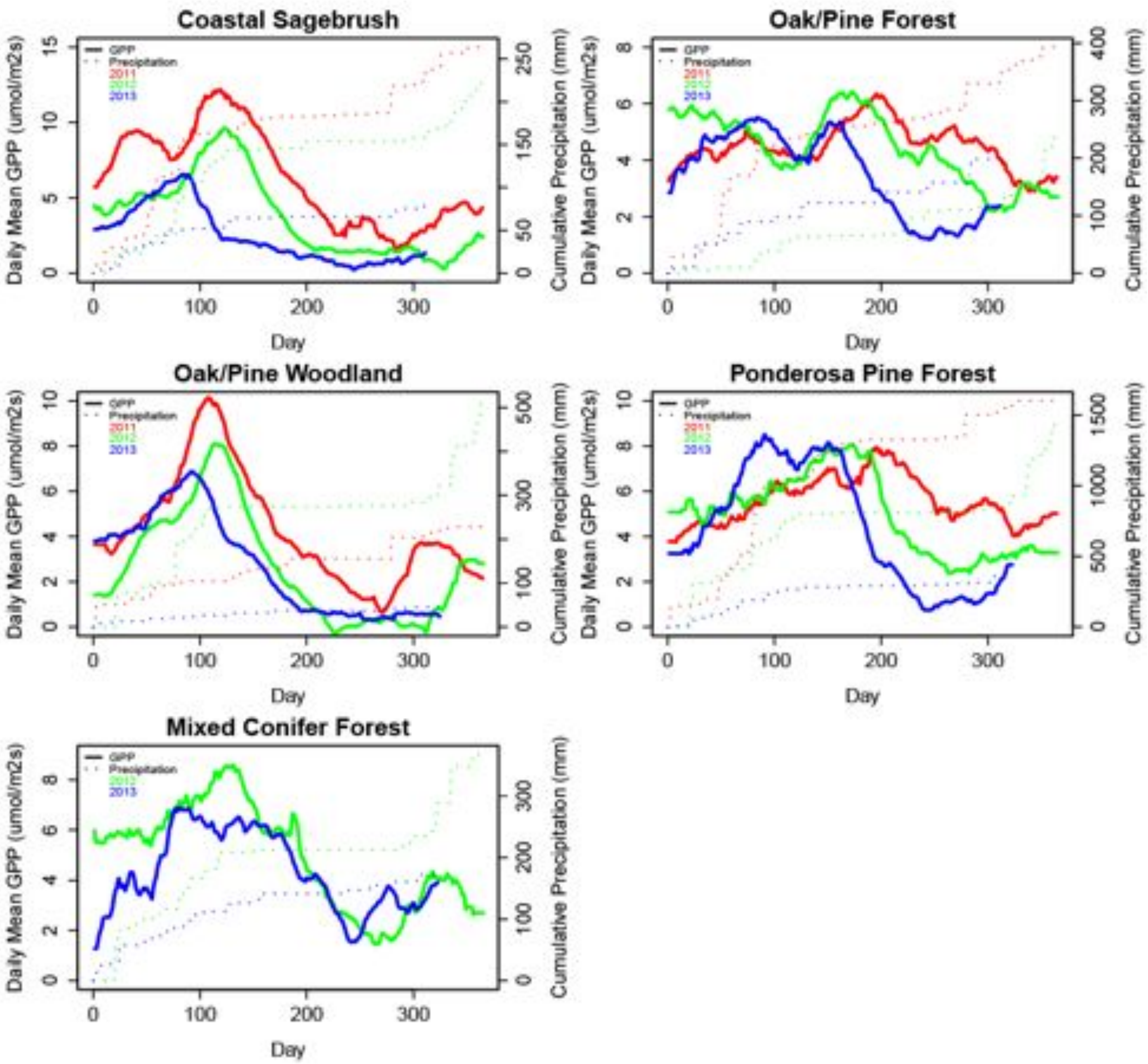

Fig 6: GPP and precipitation over the past few years for the visited flux tower sites. Sites have all experienced different levels of drought due to geography and have had varying degrees of success of maintaining productivity during such conditions. For example, the non-forested sites have observed a greater drop-off during peak productivity, while productivity for forested sites declined significantly in summer with rising water demands.

Tower-based V_{cmax} estimates loosely followed the same pattern as GPP, as seen in Table 6 where higher values were generally observed during the pre-drought conditions of 2011. However, the estimates for 2012 and 2013 were often below levels we would expect to observe from a viable plant measured via gas exchange. We have visited these sites at the time of the estimates made in Table 6, and thus have a discrepancy between the model using flux tower data and leaf level estimates. We propose that this is due to the model's inability to correctly determine water use efficiency and conductivity during drought conditions. Although the numbers may not align along the 1:1 line, we expect there to be a strong correlation between the two types of measurements.

Table 6. Comparison of <u>tower-based</u> GPP and V_{cmax} estimates for the times of AVIRIS/MASTER flight acquisitions. V_{cmax} estimates are considerably lower than those of non-drought conditions, as with GPP estimates. The GPPmax estimate is the maximum GPP estimate of any half hour during each sampling period.

Site	Year	DOY	GPPmax	Vcmax
Coastal Sage	2013	84	9.99	16.77
Oak/Pine Forest	2013	86	8.69	18.18
Oak/Pine Forest	2013	161	8.41	15.63
Ponderosa Pine Forest	2013	174	11.15	22.74
Mixed Conifer Forest	2013	172	11.26	20.36
Oak/Pine Woodland	2013	93	10.11	18.78
Oak/Pine Woodland	2013	165	3.12	4.54

We presented these results at the Global Land Project Open Science Meeting in March of 2014 in Berlin, Germany. This conference offered the opportunity for co-PI Ankur Desai and MS student Sean DuBois to discuss findings with an international and interdisciplinary audience, and increase interest in imaging spectroscopy and their potential uses. In August of 2014, new results will be presented at the Wisconsin Space Conference to experts in remote sensing and the public, allowing for popular understanding of our research and the future of spectroscopy. Current plans for year 3 include: completion of MS thesis and manuscripts on photosynthesis and drought in California ecosystems, harmonization of data for direct comparison to airborne retrievals, and continued analysis of effect of water use on V_{cmax} retrievals and GPP sensitivities.

(C) Spectral Data

We have collected a large amount of ground spectral associated with the AVIRIS/MASTER image acquisitions, as reported earlier in Table 4. Appendices A-J provide a full accounting of the sites, sampling dates, image dates and species we have measured, as well as example spectra.

Our current effort involves processing all of the spectral data (from the field and from imagery, Box 8 on Figure 3) in a consistent manner for integration, and to develop maps of biochemical and physiological properties from the image data (Boxes 6, 9, 10, 11 on Figure 3). Using results from Singh et al. (in prep.), we have generated preliminary maps of biochemical attributes and V_{cmax} based on our existing work (Box 9 on Figure 3) and estimates of V_{cmax} based on using these results with the model proposed by Kattge et al. (2009) (Box 11 on Figure 3). These have yielded maps of leaf traits and physiology that match our expectations based on field data. ***To bring our project to fruition, our primary Year 3 effort involves the comparison of image-derived estimates (illustrated below), flux-tower estimates (summarized in Table 6) and field measurements (summarized in Tables 3 and 4).*** Examples of the data that will populate these analyses are shown in Appendices K, L and M.

The standardized calibration coefficients that we are currently using to map foliar traits relevant to photosynthetic metabolism are graphed in Figure 7. These values (non-standardized) are applied on a band-by-band basis to estimate the traits of interest.

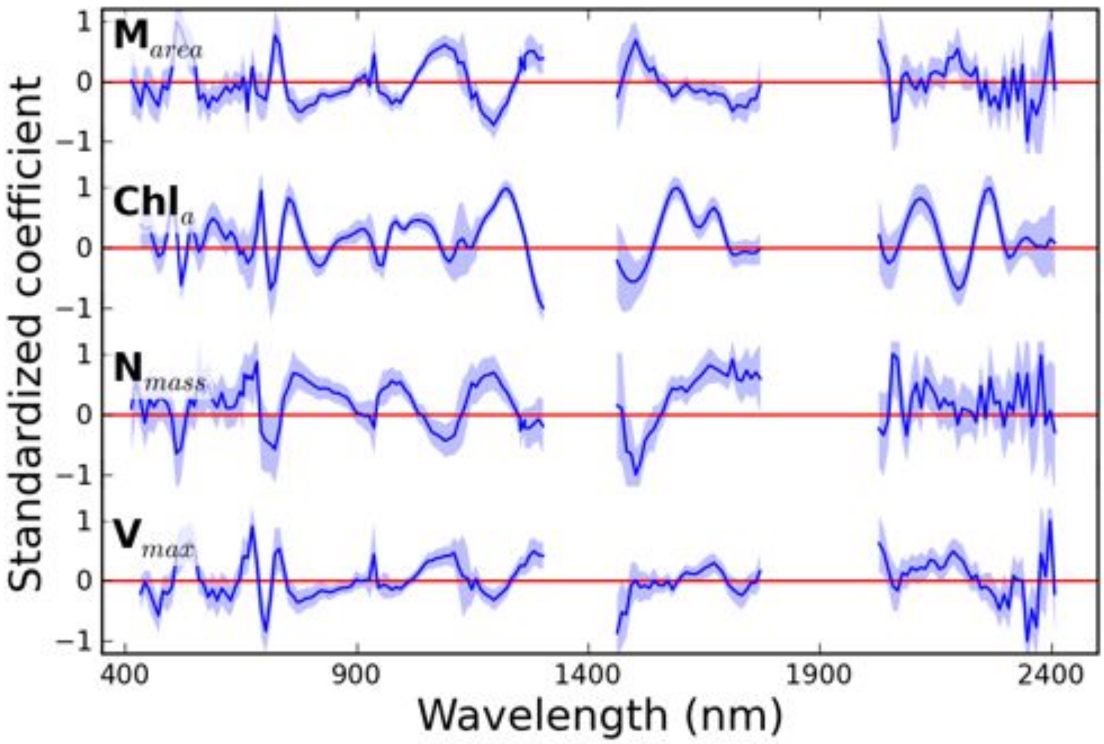

Figure 7. Standardized coefficients to estimate leaf mass per area, chlorophyll a concentration, nitrogen concentration and V_{cmax} from AVIRIS imagery.

The results of the image analyses using coefficients shown in Figure 7 are presented in Figures 8-10 below for biochemistry and Figures 11-13 for V_{cmax}. These results have not yet been validated, but the range of map predictions are consistent with our field based measurements, as illustrated in Figure 14.

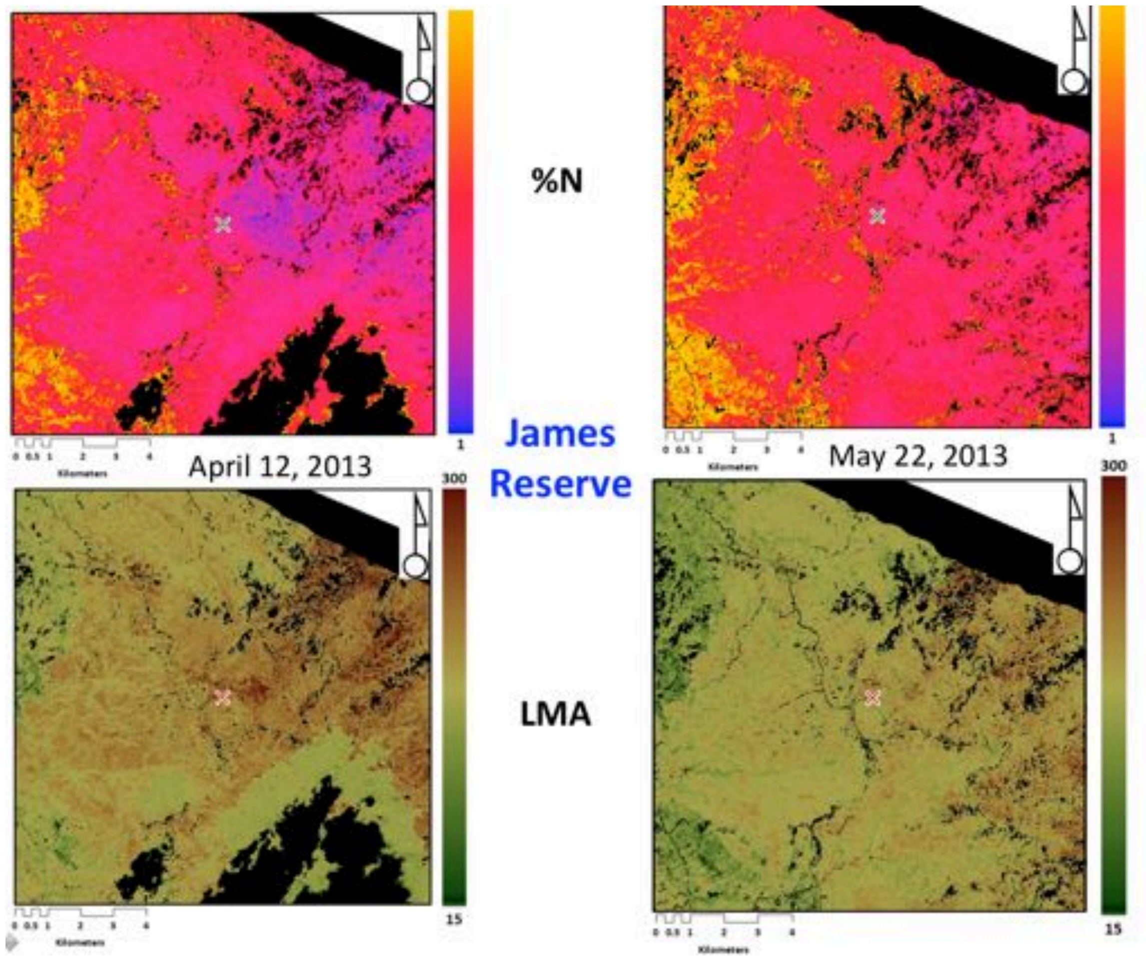

Figure 8. Nitrogen concentration and leaf mass per area for the James Reserve mixed conifer site in Southern California for two dates of AVIRIS/MASTER acquisition. Note the increasing %N and decreasing LMA from April to May as the broadleaf understory of these forests greened up.

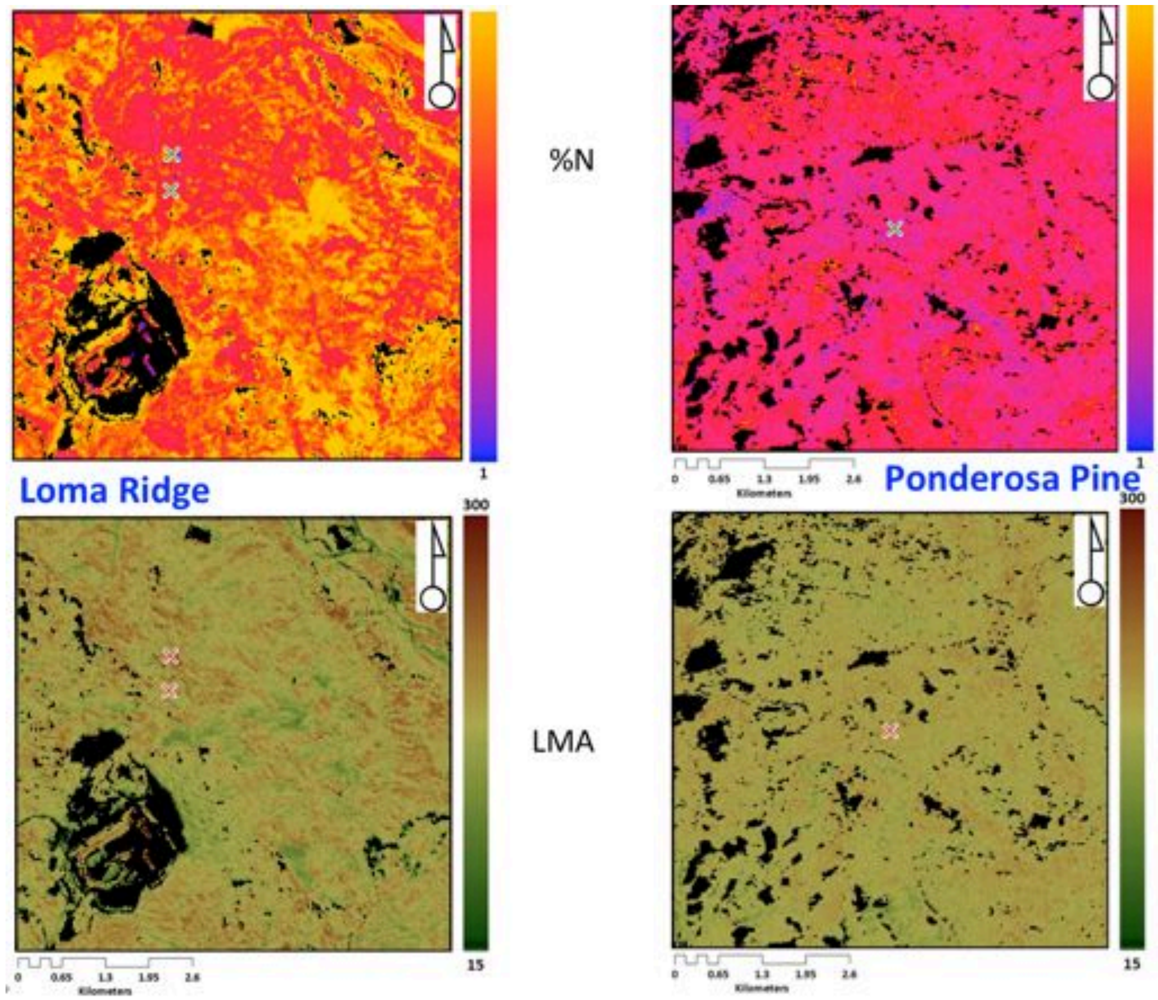

Figure 9. Nitrogen concentration and LMA for Loma Ridge coastal sage and the Sierra Ponderosa Pine site for the April 2013 acquisitions.

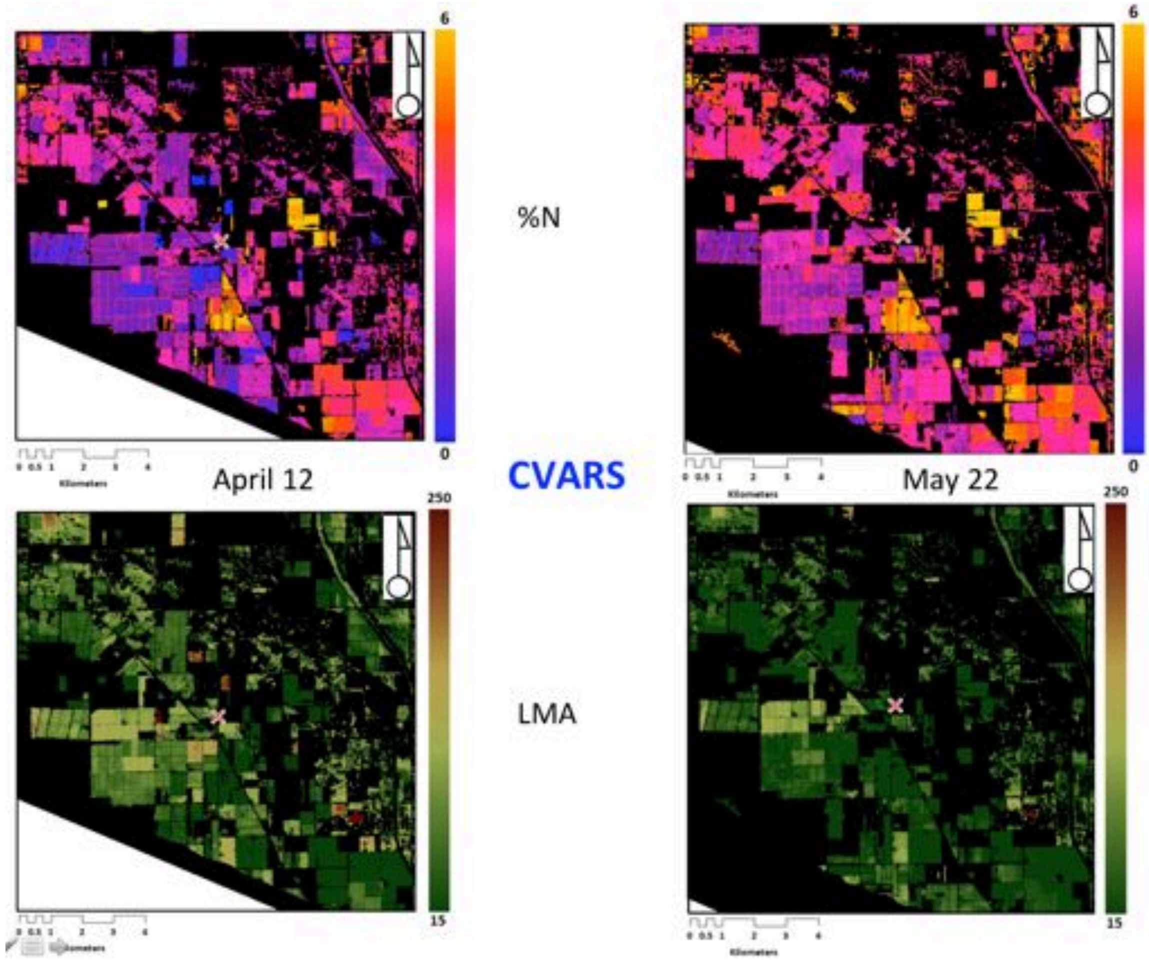

Figure 10. Nitrogen concentration and leaf mass per area for the Coachella agricultural sites for two dates of AVIRIS/MASTER acquisition. Note the seasonal differences in LMA and N concentration.

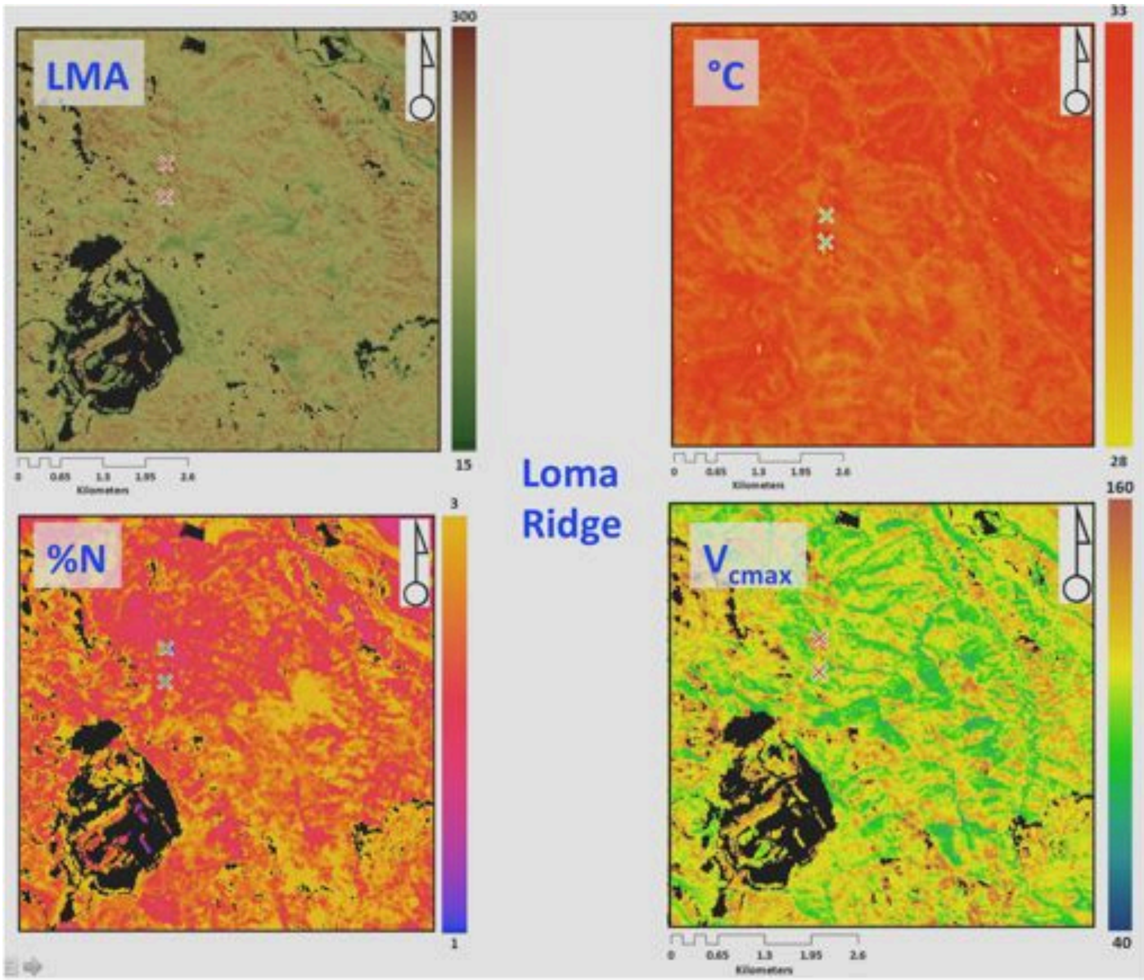

Figure 11. Lower right shows first estimate of V_{cmax} (April 2013) for the Loma Ridge coastal sage site. AVIRIS estimates of LMA and %N as well as MASTER temperature are shown for reference. Symbols indicate location of Goulden flux towers.

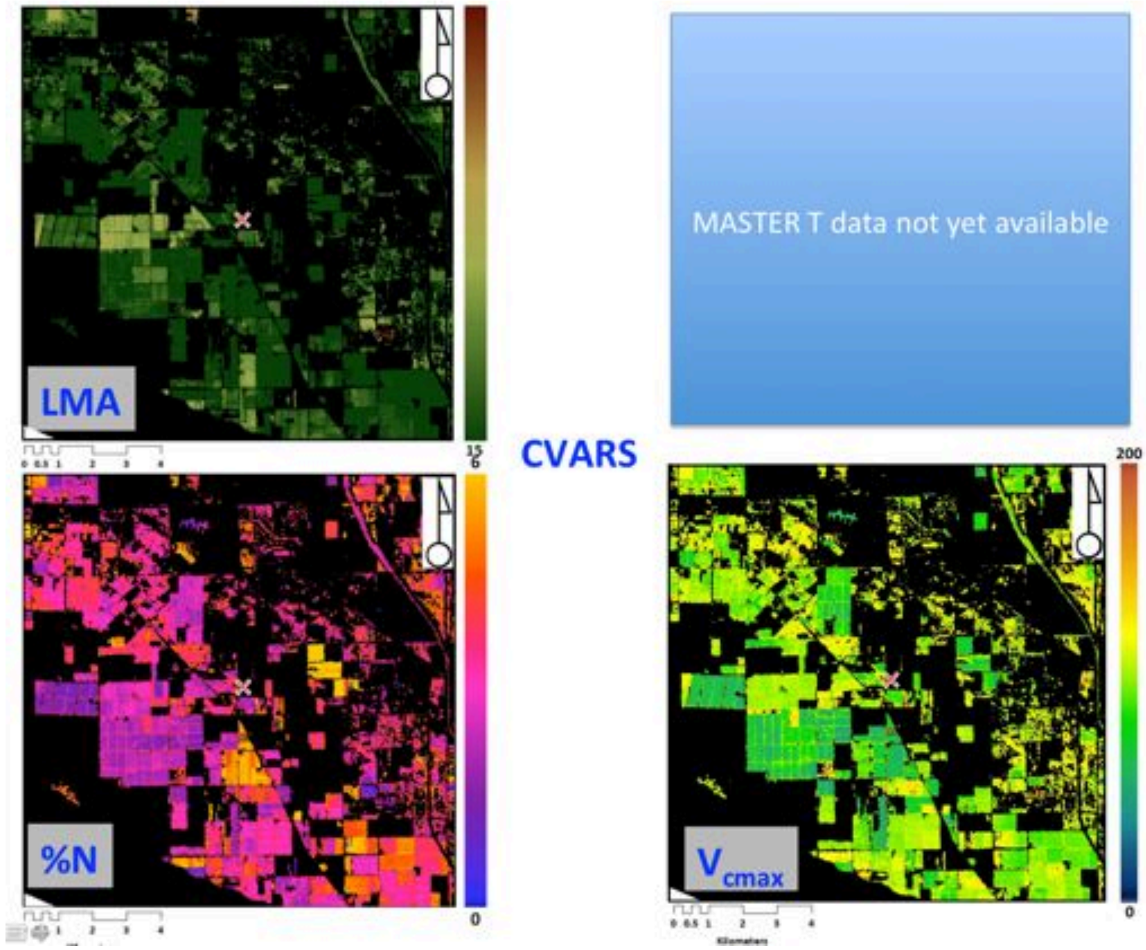

Figure 12. Lower right shows first estimate of V_{cmax} (May 2013) for the Coachella Valley agricultural sites. AVIRIS estimates of LMA and %N are shown for reference; MASTER temperature was not yet available at the time of this writing. Symbols indicate location of gas exchange measurements.

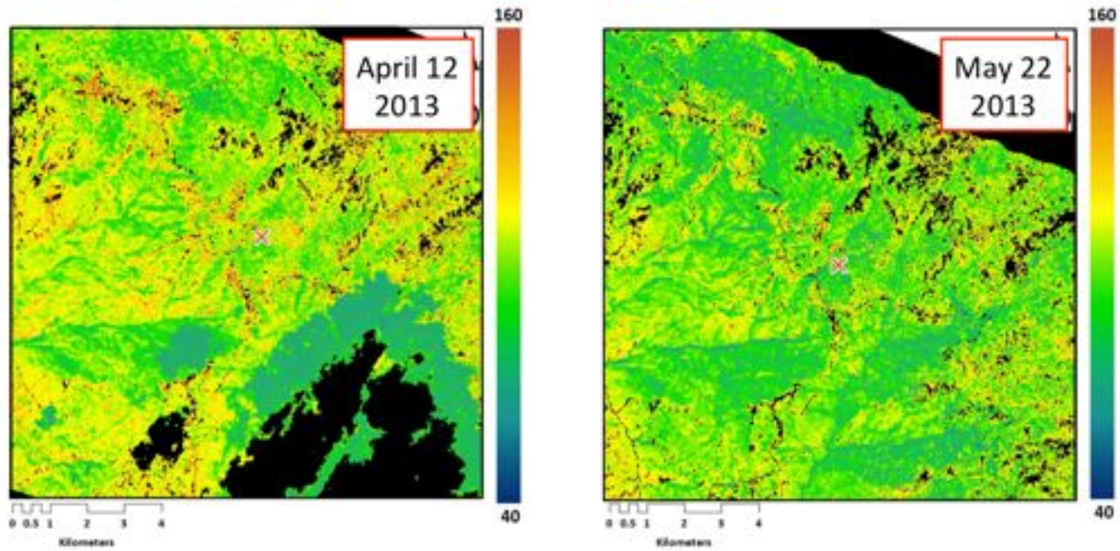

Figure 13. Preliminary estimates of V_{cmax} for the James Reserve (mixed conifer with deciduous understory) for two acquisition dates.

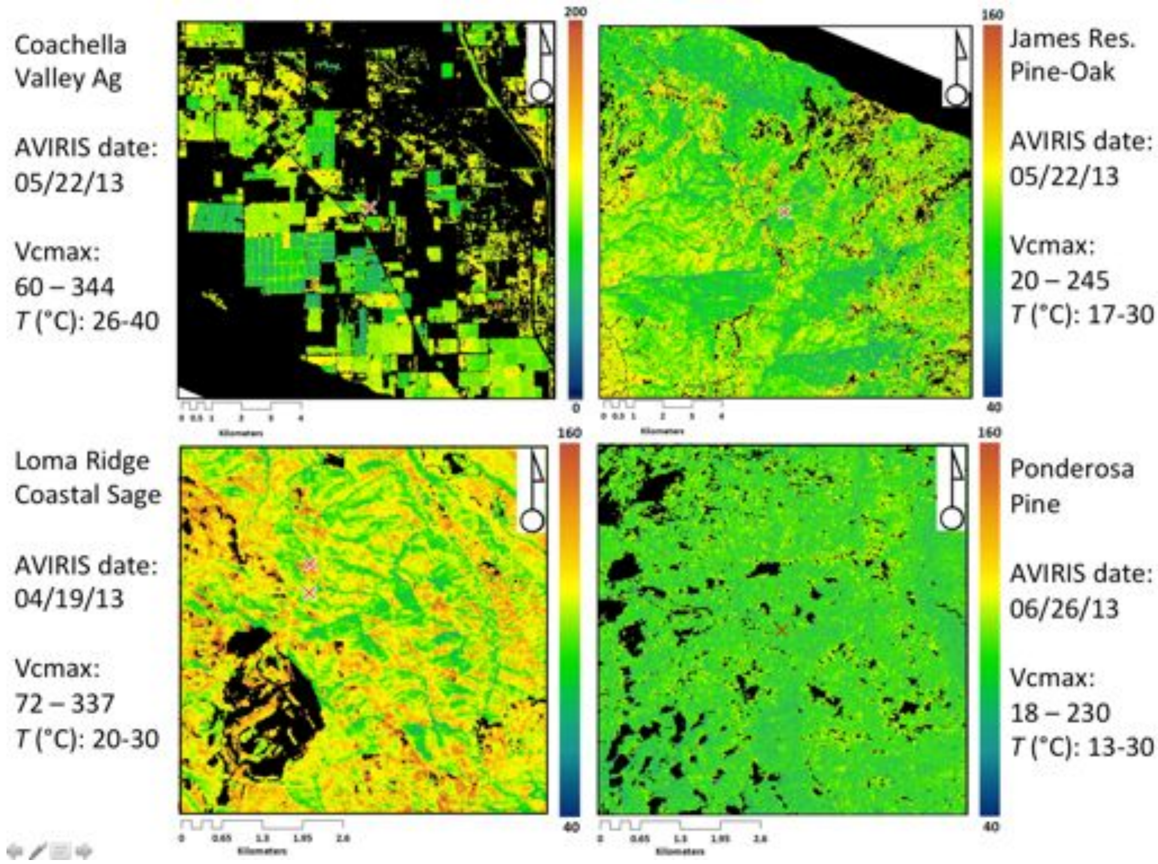

Figure 14. Preliminary comparisons of mapped estimates of V_{cmax} and field estimates.

Summary

Year 3 activities are focused on bringing together the field, image and flux tower data for comparison and corroboration. In particular, we plan to assess the extent to which image-based measurements match what should be expected from the tower-based retrievals, for towers in which we do not have field measurements. Currently, three papers from this research – led by DuBois/Desai, Townsend/Kruger, and Serbin/Townsend/Kruger are in preparation.

Collaborative Activities

In addition to data collection for our research, we have been involved in fruitful collaborations with the groups at UC-Davis (Ustin group), UC Santa Barbara (Roberts group), and Sonoma State (Clark's group). For example, we have provided a large number of foliar samples for analysis of pigment composition, including carotenoids, in order to aid in the refinement of modeling leaf optical properties. In addition, we have been collaborating with various groups to aid in the processing of spectral observations using a custom R package developed for QA/QC and processing of spectral data (R-FieldSpec; https://github.com/serbinsh/R-FieldSpec). Finally, we worked closely with the groups from NEON and RIT during the June campaign to provide canopy samples and spectral observations at the SJER and Soaproot sites.

Project Staffing

The field and analytical components of the research have been led by former UW-Madison post-doctoral research associate Shawn Serbin, who is now in faculty-level research scientist position at DOE Brookhaven National Laboratory. Dr. Serbin led all of our fieldwork in 2013 and 2014 and is coordinating the analysis of leaf-level gas exchange data with respect to spectra. Serbin has overseen all processing of field measurements.

Overall project lead is Phil Townsend, who has overseen the development of spectroscopic protocols and participated in fieldwork. Townsend leads the AVIRIS processing activities. Townsend has worked with Serbin to explore methods of scaling leaf-level spectroscopic estimation of metabolic capacity to AVIRIS spectra.

Eric Kruger has coordinated planning and logistics activities and participated in fieldwork. In addition to analyzing and interpreting gas-exchange data of V_{cmax} and J_{max}, Kruger has been exploring other facets of the gas exchange data, such as possible links between stomatal conductance and estimates of electron transport rate, which, in turn, may be estimable from leaf reflectance spectra.

Ankur Desai has overseen the collection and analysis of eddy covariance (EC) flux data used to evaluate HyspIRI-derived retrievals. Processing of EC data is conducted by MS student Sean DuBois, under supervision of Desai.

New UW-Madison MS student Andrew Jablonski – under the supervision of Townsend and Kruger – has taken on responsibility for image processing and overall data integration, as well as fieldwork.

In addition, we have been assisted by Clayton Kingdon (research specialist: fieldwork, spectroscopy, image processing), Ryan Sword (MS student), Ryan Geygan (research intern: fieldwork), Ben Spaier (LTE: fieldwork), and Robert Phetteplace (undergraduate: fieldwork and image processing).

Conference Presentations

Ankur R. Desai, Sean DuBois, Shawn P. Serbin, Toni T. Viskari, Michael C. Dietze, and Philip A. Townsend, 2013. *Advancing techniques for informing terrestrial ecosystem models with leaf and imaging spectroscopy to improve the representation and prediction of vegetation dynamics and carbon cycling*, EuroSpec 2013 Final Conference, November 6-8 (Trento, Italy).

DuBois, S., Serbin, S., Desai, A., Kruger, E., Kingdon, C., Goulden, M., Townsend, P. (2013). *Measurement of ecosystem metabolism across climatic and vegetation gradients in California*, American Geophysical Union Fall Meeting, San Francisco, CA. (Poster)

DuBois, S.G., Desai, A.R., Serbin, S.P., Townsend, P.A., Kruger, E.L., Kingdon, C.C., (2014) The use of hyperspectral imagery to assess the sensitivity of ecosystem photosynthetic parameters along two California climate gradients, Global Land Project Open Science Meeting, Berlin, Germany (Poster) [also presented at University of Wisconsin Earth Day Conference, April 21, 2014]

Serbin, S.P., DuBois, S.G., Desai, A.R., Kruger, E.L., Kingdon, C.C., Goulden, M.L., Townsend, P.A. (2013). *Characterizing ecosystem metabolism across climatic and vegetation gradients in California as part of the NASA HyspIRI Airborne Campaign,* NASA HyspIRI Workshop, Pasadena, CA. (Poster)

Serbin, S.P. (2014) *An introduction to spectroscopy and capturing spatial variation in terrestrial carbon cycling*, Mechanisms and Interactions of Climate Change in Mountain Regions (MICMoR) Summer School, July 21-30th, KIT/IMK-IFU, Garmisch-Partenkirchen, Germany.

Shawn P. Serbin; Michael Dietze; Ankur R. Desai; David LeBauer; Toni Viskari; Rob Kooper; Kenton G. McHenry; Philip A. Townsend, 2013. *Assimilation of Leaf and Canopy Spectroscopic Data to Improve the Representation of Vegetation Dynamics in Terrestrial Ecosystem Models*, American Geophysical Union (AGU) Fall Meeting, December 9-13 (San Francisco).

Aditya Singh, Shawn P. Serbin, Clayton C. Kingdon, Philip A. Townsend, 2013. *Scaling, propagating and mapping uncertainty in spectroscopy-derived foliar traits from the leaf to the image*, 2013 HyspIRI Science Workshop, October 15-17, 2013 (Pasadena, CA).

Townsend, P.A., Serbin, S.P., Kruger, E.L., DuBois, S.G., Desai, A.R., Jablonski, A., Singh, A. *Imaging spectroscopy of plant physiology*, NASA HyspIRI Airborne Science Team Meeting, March 17^{th} – 18^{th}, NASA Headquarters, Washington DC (Presetation)

Philip A. Townsend, Shawn P. Serbin and Eric L. Kruger, 2013. *Leaf- and canopy-level reflectance spectroscopy show potential to estimate plant photosynthetic capacity*, 16th International Congress on Photosynthesis, August 14-16 (St. Louis, MO).

Philip A. Townsend; Shawn P. Serbin; Clayton Kingdon; Aditya Singh; John J. Couture; John A. Gamon, 2013. *Spectral Data Captures Important Variability Between and Among Species and Functional Types*, American Geophysical Union (AGU) Fall Meeting, December 9-13 (San Francisco).

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Ainsworth, E.A., Serbin, S.P., Skoneczka, J.A. & Townsend, P.A. (2013). Using leaf optical properties to detect ozone effects on foliar biochemistry. *Photosynthesis Research*, DOI: 10.1007/s11120-013-9837-y.

Goulden, M.L., Anderson, R.G., Bales, R.C., Kelly, A.E., Meadows, M., & Winston, G.C. (2012). Evapotranspiration along an elevation gradient in California's Sierra Nevada. *Journal of Geophysical Research-Biogeosciences, 117*

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Singh, A., Serbin, S.P., Kingdon, C.C., McNeil, B.E., & Townsend, P.A. (In prep.) A generalized method for the mapping of canopy foliar biochemical and morphological traits using imaging spectroscopy. *Remote Sensing of Environment*.

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Appendix A. Summary of species sampled at agricultural sites.

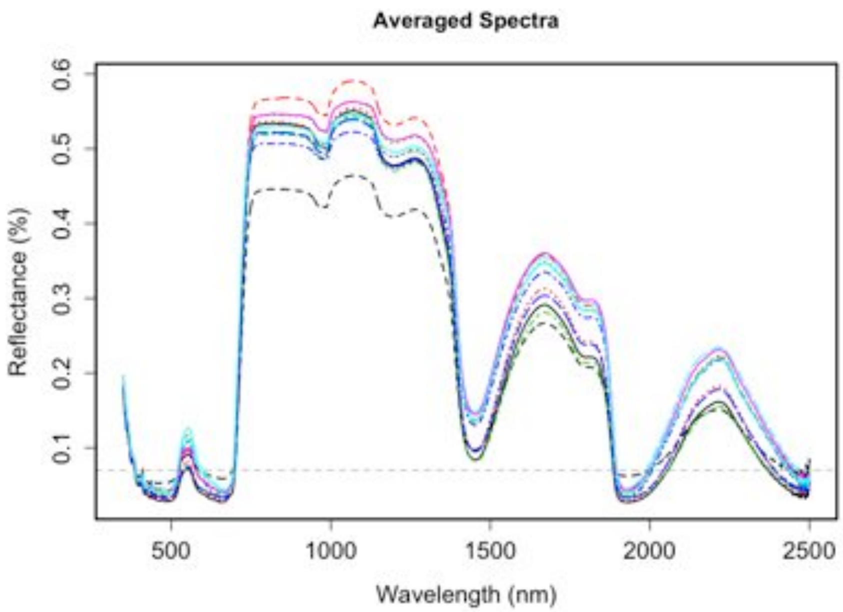
Agricultural Sites

Site	Species	Code	Date	Spectra Types
CVARS	Red Pepper	CAAN	2013, 2014	Leaf, IS, Canopy
CVARS	Lemon		2013, 2014	Leaf, IS, Canopy
CVARS	Grape		2013	Leaf, IS
CVARS	Short Date		2014	Leaf, IS
CVARS	Mature Date		2014	Leaf, IS, Canopy
CVARS	Mandarin Orange		2014	Leaf, IS, Canopy
CVARS	Bare Field		2014	Canopy
KARE	Pistachio		2013	Leaf, IS
KARE	Young Oats		2014	Leaf, IS, Canopy
KARE	Mature Oats		2014	Leaf, IS, Canopy
KARE	Peach		2014	Leaf, IS
KARE	Pomegranate		2014	Leaf, IS, Canopy
Kingsburg	Almond		2014	Leaf
Kingsburg	Peach		2014	Leaf, Canopy
Motte Rimrock	Orange	orng	2013	Leaf
SCREC	Avocado	AVCD/PEAM	2013	Leaf,IS,Canopy

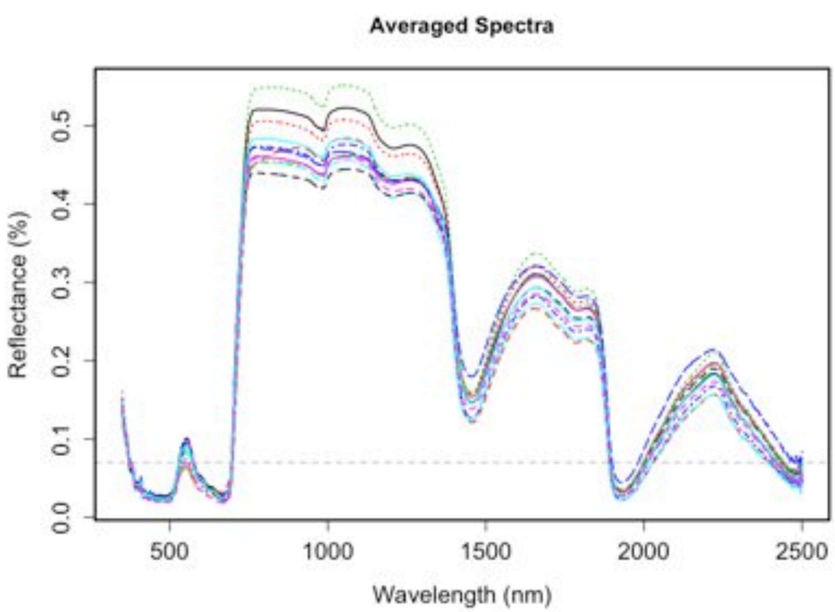
Appendix B. Summary of image acquisition dates for agricultural sites.

Site	Scene Date
CVARS/SCREC	3/29/2013
CVARS/SCREC	4/12/2013
CVARS/SCREC	4/19/2013
CVARS/SCREC	5/22/2013
CVARS/SCREC	9/24/2013
Kingsburg/KARE	5/3/2013
Kingsburg/KARE***	6/12/2013
Kingsburg/KARE	9/19/2013

Appendix C. Example spectra from red pepper.



Appendix D. Example spectra from avocado.



Appendix E. Summary of species sampled at natural vegetation sites along the climate-elevation transect in the Sierras.

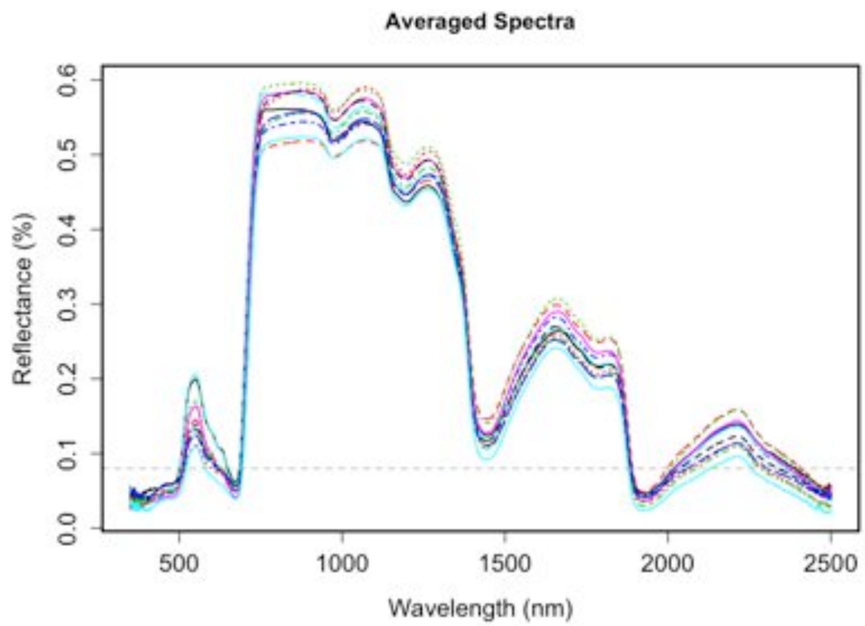
Sierra Nevada Sites

Site	Species	Code	Date	Spectra Types
MCON	Sugar Pine	PILA	2013, 2014	Leaf,IS
MCON	White Fir	ABCO	2013, 2014	Leaf,IS
MCON	Incense Cedar	CADE	2013	Leaf,IS
MCON	Manzanita	Manz	2013, 2014	Leaf,IS,Canopy
MCON	Jeffrey Pine	PIJE	2013	Leaf
MCON	California Black Oak	QUKE	2013	Leaf,IS
MCON	Whitethorn ceanothus	CECO	2013	Leaf,IS
NEON	Ponderosa Pine	PIPO	2014	IS
SJER	Interior Oak	QUWI	2013	Leaf,IS
SJER	Digger Pine	PISA	2013	Leaf,IS
SJER	Blue Oak	QUDO	2013	Leaf,IS
SJER		CECU	2013	Leaf,IS
SJER	Manzanita	Manz	2013	Leaf,IS
SJER	Live Oak Mistletoe		2013	Leaf,IS
SOAPROOT	Incense Cedar	CADE	2013, 2014	Leaf,IS
SOAPROOT	Manzanita	MANZ	2013	Leaf,IS
SOAPROOT	Ponderosa Pine	PIPO	2013, 2014	Leaf,IS
SOAPROOT	Canyo Oak	QUCH	2013, 2014	Leaf,IS

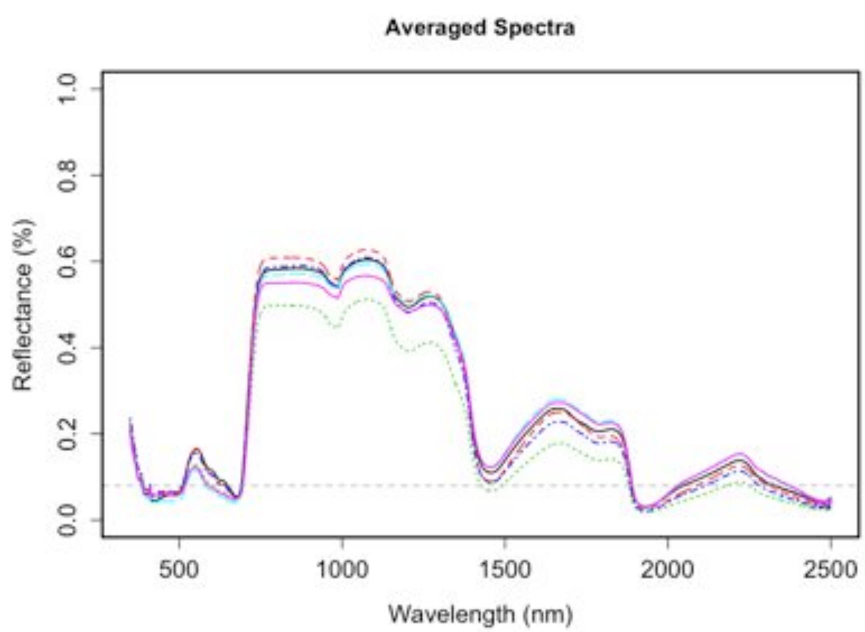
Appendix F. Summary of image acquisition dates for natural vegetation sites along the climate-elevation transect.

Site	Scene Date
SJER/MCON/SOAP	5/3/2013
SJER/MCON/SOAP	6/12/2013
SJER/MCON/SOAP	6/26/2013
SJER/MCON/SOAP	11/5/2013

Appendix G. Example spectra of ponderosa pine and incense cedar.



Appendix H. Example spectra of white fir and sugar pine.



Appendix I. Summary of species sampled at natural vegetation sites in Southern California.

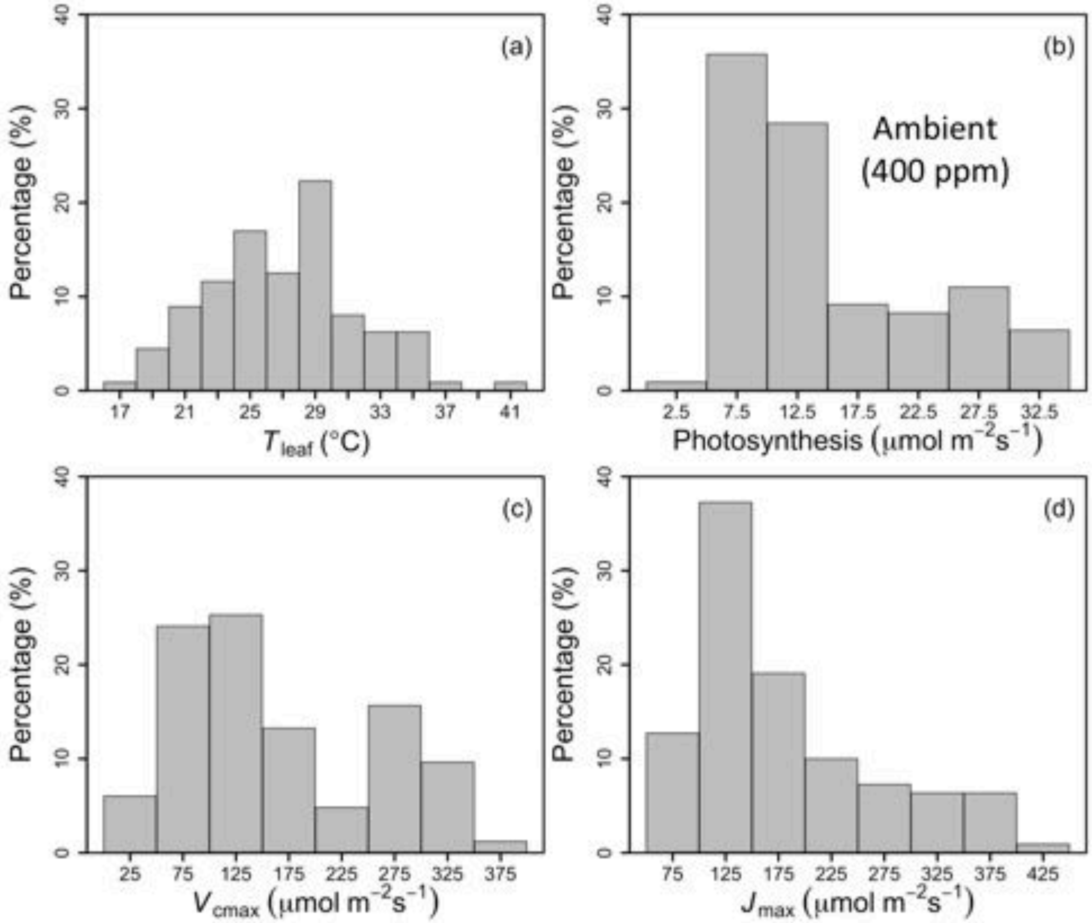
Southern California

Site	Species	Code	Date	Spectra Types
LOMA RIDGE	Black Sage	BS	2013	Leaf,IS,Canopy
LOMA RIDGE	Laurel Sumac	LS	2013	Leaf,IS
LOMA RIDGE	Rye Grass	RYE	2013	Leaf,IS
LOMA RIDGE	White Sage	WS	2013	Leaf, IS, Canopy
LOMA RIDGE	Artemisia	ARTM	2013	Leaf, IS, Canopy
SJJR	Interior Oak	QUWI	2013, 2014	Leaf,IS
SJJR	Manzanita	Manz	2013, 2014	Leaf,IS
SJJR	Coulter Pine	PICO	2013, 2014	Leaf,IS
SJJR	Ponderosa Pine	PIPO	2014	Leaf,IS
SJJR	Sugar Pine	PILA	2013, 2014	Leaf,IS
SJJR	Canyon Oak	QUCH	2013, 2014	Leaf,IS
SJJR	Incense Cedar	CADE	2013, 2014	Leaf,IS

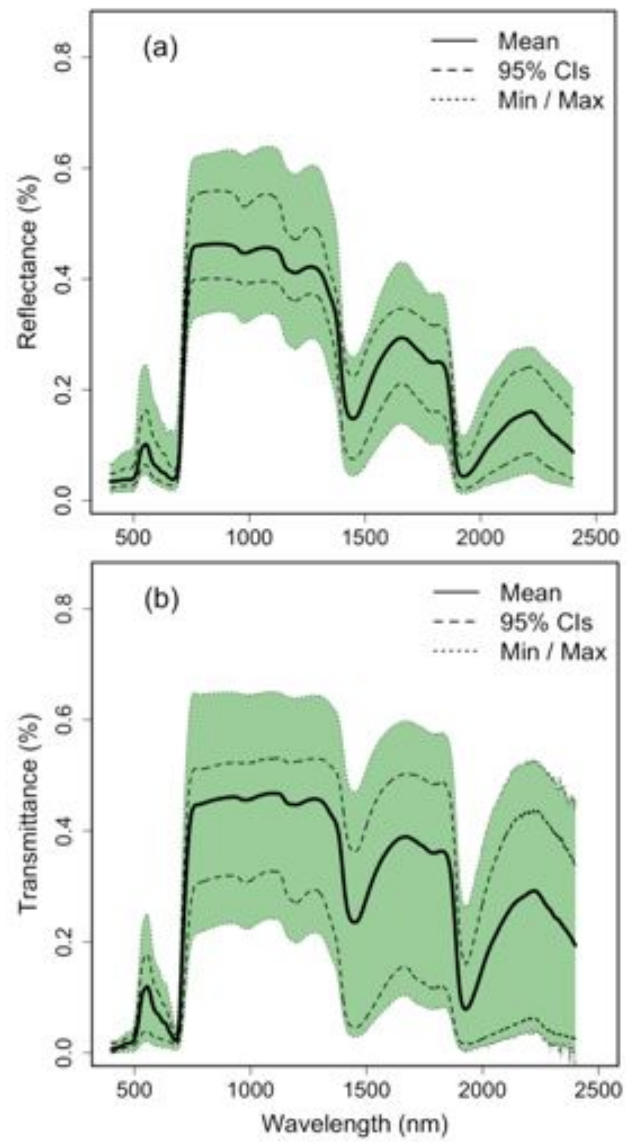
Appendix J. Summary of image acquisition dates for natural vegetation sites sites in Southern California.

Site	Scene Date
SJJR/Loma Ridge	3/29/2013
SJJR/Loma Ridge	4/12/2013
SJJR/Loma Ridge	4/19/2013
SJJR/Loma Ridge	5/22/2013
SJJR/Loma Ridge	9/24/2013

Appendix K. Distribution from our data of (a) leaf temperature, (b) photosynthesis, (c) V_{cmax}, and (d) J_{max} rates from our field data.



Appendix L. Full summary of spectra collected in our study, including (a) Reflectance and (b) leaf transmittance.



Appendix M. (a) Example A-Ci curve used to derive V_{cmax} and J_{max} [where A refers to assimilation rate and Ci is interstitial CO_2 concnetration, i.e. photosynthesis, derived from gas exchange] and (b) Example ETR-Ci curve used to derive J_{max} [where ETR refers to electron transport rate determined from the fluorescence head attachment to the LI-6400 instrument used to measure gas exchange.]